9.1 Two Models for Light

SECTION EXPECTATION

- Define and explain the units and concepts related to the wave nature of light.

KEY TERMS

- dispersion
- diffraction
- Huygens' principle
- superposition of waves
- constructive interference
- destructive interference
- nodal point

You flip a switch as you walk into a room, flooding the room with light that instantly reaches every corner. Objects in the path of the light generate shadows, and yet the light reaches far enough under your bed to illuminate an old shirt. What allows light to seemingly be everywhere instantaneously, be blocked by objects, and yet be able to reflect and bounce into tiny nooks and crannies?

Physicists have been trying to develop a complete model of light for centuries. Is light best modelled as a particle or as a wave? These competing models for light originated in the late 1600s, proposed by physicists who were attempting to describe the propagation of light.

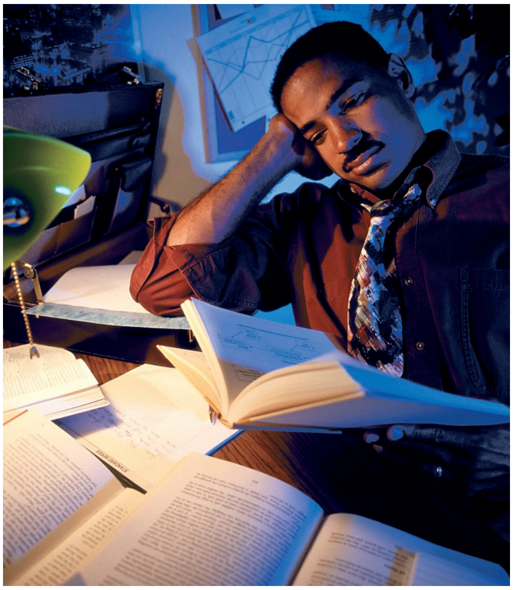

Figure 9.1 Even though the light casts shadows, you can still clearly see objects in those shadows. A little light seems to reach everywhere.

The basic properties of light that were understood in the 1600s (and that any acceptable model must be able to explain) were straight-line propagation, reflection, refraction, dispersion, and the ability of light to travel undisturbed across millions of kilometres of space. Which model — particle or wave — could best explain and predict these properties?

Newton's Corpuscular Model

Although scientists and philosophers had been hypothesizing about the nature of light for centuries, Sir Isaac Newton (1642–1727) was the first to formulate a detailed, systematic model of light. He published his "corpuscular" theory of light in 1704. Newton's proposed corpuscles were particles with exceedingly small masses that travelled in straight lines through space,

penetrated some media, and bounced off other solid surfaces. Newton could explain refraction (the bending of light when it travels from one medium to another) if the speed of the particles increased when entering a more-dense medium. Although speeding up in a dense medium does not seem logical, Newton explained it by proposing that an attractive interaction existed between the light particles and the medium.

Conceptual Problem

- Use the conservation of momentum to show that when a particle such as a billiard ball collides with a solid wall, it follows the law of reflection, which states that the angle of reflection is equal to the angle of incidence.

The **dispersion** of light, which is the separation of light into the colours of the spectrum when passing through a prism, had been observed by scientists before Newton proposed his theory of light. Newton himself had demonstrated that white light was actually a composite of all of the colours of the rainbow by showing that the colours could be combined by a second prism and produce white light.

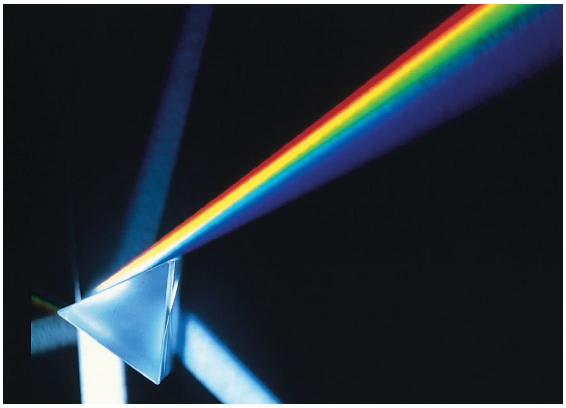

Figure 9.2 Using a refracting prism, white light can be separated into a spectrum of colour.

According to Newton's corpuscular model, each colour had a different mass. Violet light was refracted the most and therefore must have the least amount of mass, making it easiest to divert from its original path. Blue light was more massive than violet and therefore refracted less. Following this argument, Newton assumed that red light particles were the most massive of all of the visible colours.

Another question that Newton's corpuscular theory was able to answer was: What occupies the space between Earth and the Sun? If light was, in fact, small particles of insignificant mass, the particles would be able to travel millions of kilometres to Earth from the Sun. Possibly, the most important reason that Newton did not consider the wave model for light was the apparent lack of

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diffraction — the spreading of a wave after encountering a barrier. Italian scientist Francesco Grimaldi (1606–1680) provided evidence that light does undergo diffraction by demonstrating that light passing through a small opening in a barrier produced a spot of light on a distant screen that was larger than strict ray diagrams predicted. The edges of the bright spot also appeared fuzzy: The region of light faded into dark, rather than being crisply divided into two regions. Newton and the proponents of the corpuscular theory of light discounted the effects, citing that the amount of diffraction seemed to be too small to be of consequence.

Newton was not entirely convinced of the correctness of his own corpuscular model for light and was surprised that some of his proponents approved of it so strongly. Nevertheless, until stronger evidence of wave-like properties was obtained, Newton would not accept a wave model for light.

Huygen's Wave Model

Christiaan Huygens (1629–1695) refined and expanded the wave model of light, originally proposed by Robert Hooke (1635–1703). Hooke rejected a particle model partly because two beams of light can pass through each other without scattering each other, as particles do. One problem with the wave model was the ability of light to travel through the apparently empty space of the universe.

During early discussions about the nature of light, scientists knew that mechanical waves required a medium through which to propagate. Various properties of the medium would undergo periodic changes from a maximum, to an equilibrium, to a minimum, and back through the cycle again. For example, in a water wave, the particles of water actually move between a maximum and minimum height. In sound waves, the pressure of the medium increases and decreases. What medium could be carrying light energy? Since no medium was known to exist throughout space, scientists proposed that an as yet undetected medium called "ether" existed to carry light waves.

Huygens developed a priniciple that is still helpful in analyzing and predicting the behaviour of waves. He compared the propagation of light to the travelling disturbance observed when a pebble is dropped into a pond of still water. The disturbance, or wave pulse, moves outward in concentric circles from the pebble's point of impact. Huygens realized that the waves travelling outward from the centre continue to travel even after the pebble has struck the pond's bottom. The waves are effectively travelling without a source.

Extending this example, he postulated that disturbances existing at each point on a wavefront could be a source for disturbances along the wavefront an instant later. Figure 9.3 illustrates Huygens' thinking for straight and circular waves.

PHYSICS FILE

Robert Hooke contributed to science in several fields, from cellular biology to the physics of light. Hooke developed the wave theory of light, while Newton proposed the corpuscular or particle theory of light. Hooke and Newton had argued before, because Hooke had developed an early version of Newton's gravitation equation and felt that Newton had not given him enough credit. Both men realized, however, that more evidence would be necessary before either of their models would be accepted.

Huygens' principle states: Every point on an advancing wavefront can be considered to be a source of secondary waves called "wavelets." The new position of the wavefront is the envelope of the wavelets emitted from all points of the wavefront in its previous position.

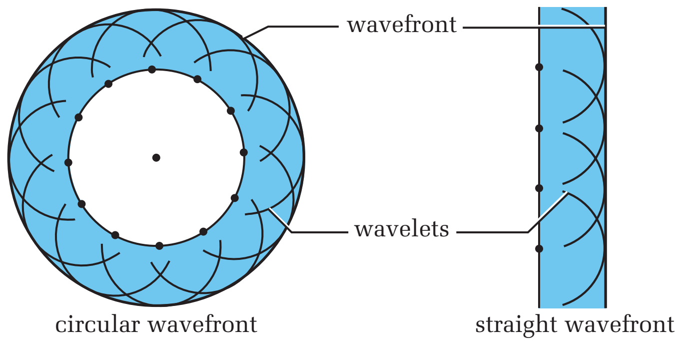
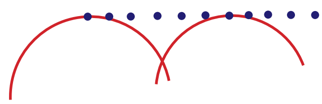


Figure 9.3 Each point of a wavefront can be considered to be a source of a secondary wave, called a "wavelet."

Conceptual Problem

- Carefully mark a small dot every 0.5 cm over a distance of 8.0 cm on a blank sheet of white paper. Beginning with the first dot, use a 25 cent coin to draw semicircles on every fourth dot. Ensure that each semicircle arc is drawn with the leading edge always closest to the top of the page, intersecting a single dot as shown. Draw more arcs, one for each dot.
  (a) Does the leading edge of the sum of the arcs form a more complete wavefront?
  (b) Would an infinite number of wavelets form a continuous wavefront? What is happening behind the wavefront to cause a single wavefront to form?



Either by applying Huygens' principle or by observing visible waves such as water waves, you can show that waves propagate in straight lines while moving unobstructed through a single medium, and that they reflect off solid or opaque barriers. Huygens also showed that if the velocity of light decreases when it passes from a less-dense to a more-dense medium, it will bend or refract in such a way that the angle of refraction is smaller than the angle of incidence. A slight difference in the speed of the various colours of light in a given medium could also explain dispersion.

Huygens' wave model accurately predicted the behaviour of light as strongly or even more strongly than did Newton's model in terms of rectilinear propagation, reflection, refraction, and

dispersion. At that time, however, there were no tests or observations that could eliminate either model, so Newton's stature in the scientific community (gained for his many and varied contributions, including the laws of motion) resulted in his winning the approval of other scientists for his less eloquent corpuscular model. What type of experiment would be necessary in order to accept or reject one of the models? What would reveal the greatest contrast between the properties of waves and particles?

Superposition of Waves

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The superposition of waves principle holds true for linear waves. Linear waves are characterized by small amplitudes. Interestingly, the superposition principle does not apply to non-linear waves, characterized by large amplitudes. This textbook does not deal with non-linear waves.

What happens when two particles or two waves attempt to occupy the same point in space at the same time? Obviously, as two particles approach the same point, they will collide and move in a way that will obey the law of conservation of momentum. Two waves, however, *can* occupy the same space at the same time. When two waves pass through one location in the medium, the medium will oscillate in a way that resembles the sum of the effects from both waves. Waves that reach the same point simultaneously interfere with each other in terms of the displacement of the medium.

This result, called the **superposition of waves**, is formally stated as: When two or more waves propagate through the same location in a medium, the resultant displacement of the medium will be the algebraic sum of the displacements caused by each wave. Each wave behaves as though the other did not exist and, once past the area of interest, proceeds unchanged.

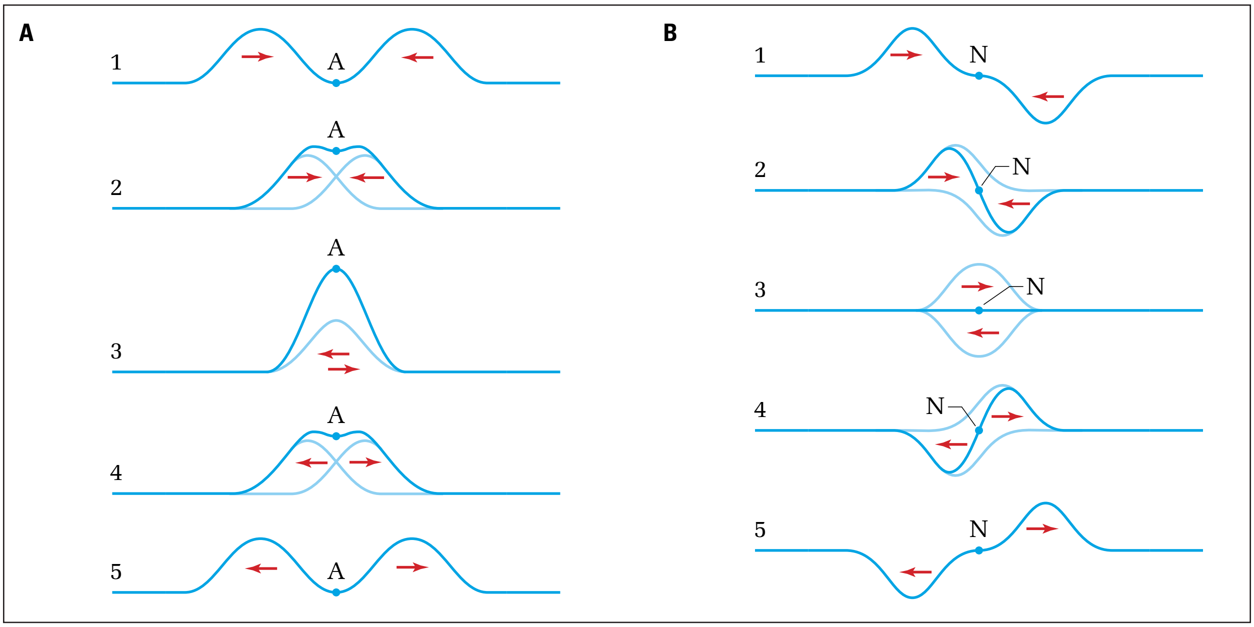

Figure 9.4 **(A)** Constructive interference results in a wave pulse that is larger than either individual pulse. **(B)** Destructive interference results in a wave pulse that is smaller than the larger of the component waves. Two identical but inverted pulses will yield a momentary amplitude of zero.

The resultant displacement of the medium caused by the superposition of two waves is unlike either of the individual waves that added together to form it. Figure 9.4 (A) illustrates two pulses travelling toward each other. The darkened wave at point A is the result of **constructive interference** of the two pulses. Constructive interference results in a wave with larger amplitude than any individual wave. Perfectly constructive interference occurs when waves are completely in phase with each other. Figure 9.4 (B) illustrates **destructive interference**. In this case, the resultant wave amplitude is smaller than the largest component wave. A **nodal point** exists in the medium when two waves with identical but inverted amplitudes exist simultaneously. The resultant displacement at a nodal point is zero.

The most definitive test of a phenomenon that could classify it as a wave is to show that it undergoes interference. In the next section, you will learn how to observe and verify that light exhibits interference and therefore must behave like a wave.

9.1 Section Review

1. MC Sound, a form of energy, can be modelled by using two distinctly different approaches.
   - **(a)** Describe the propagation of sound energy through air by discussing the motion of individual particles. Include possible mathematical equations that might apply.
   - **(b)** Describe the propagation of sound energy through air by discussing waves. Include possible mathematical equations that might apply.
   - **(c)** Does one method provide a more easily understood explanation?
   - **(d)** Does one method provide a more simple mathematical model?
2. K/U Describe Huygens' concept of wavelets.
3. **(a)** K/U Draw a series of Huygens wavelets so that they produce a circular wavefront.
   - **(b)** Describe how the wavelets that form the wavefront apparently vanish behind it.
4. **(a)** MC Do you believe that some current accepted scientific models or theories might be held in high regard because of the stature of the scientists who proposed them?
   - **(b)** Suggest one possible model or theory that is currently accepted by a majority of people that you feel might be significantly inaccurate. Explain.

UNIT PROJECT PREP

An FM transmitter produces a carrier wave with a specific frequency. A fixed frequency wave of any type is produced by periodic motion of a source.

- Hypothesize about what might experience periodic motion in the creation of FM radio waves.
- How is an understanding of frequency important in the construction of a radio transmitter?
- Apply Huygens' wave model to various waves with which you are familiar as you study this unit. Can his model predict the behaviour of all waves?